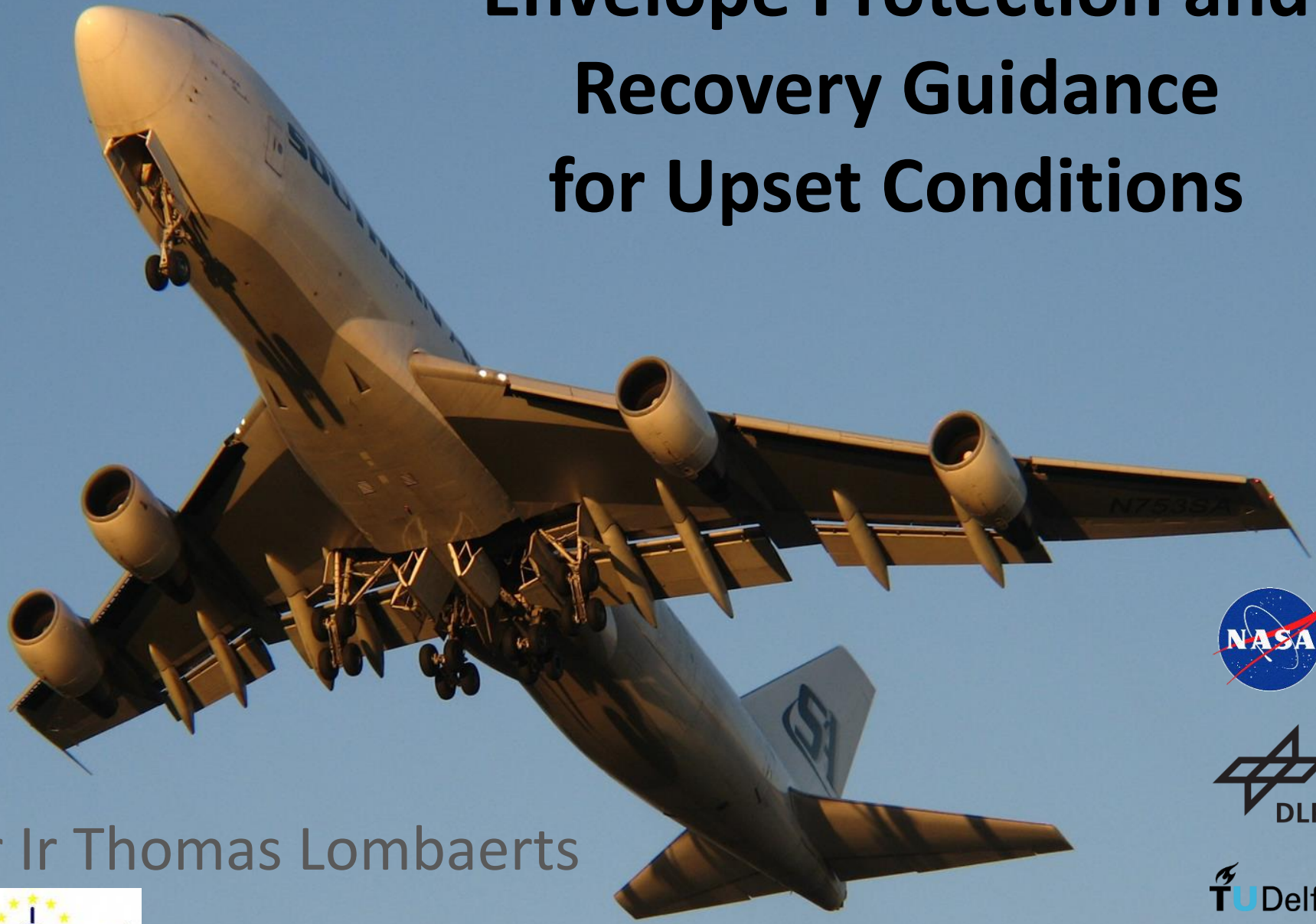
Envelope Protection and Recovery Guidance for Upset Conditions



Dr Ir Thomas Lombaerts

RECONFIGURE Final Workshop, Toulouse, June 1 – 3, 2016

Envelope Protection and Recovery Guidance for Upset Conditions



Dr Ir Thomas Lombaerts

RECONFIGURE

NASA

DLR

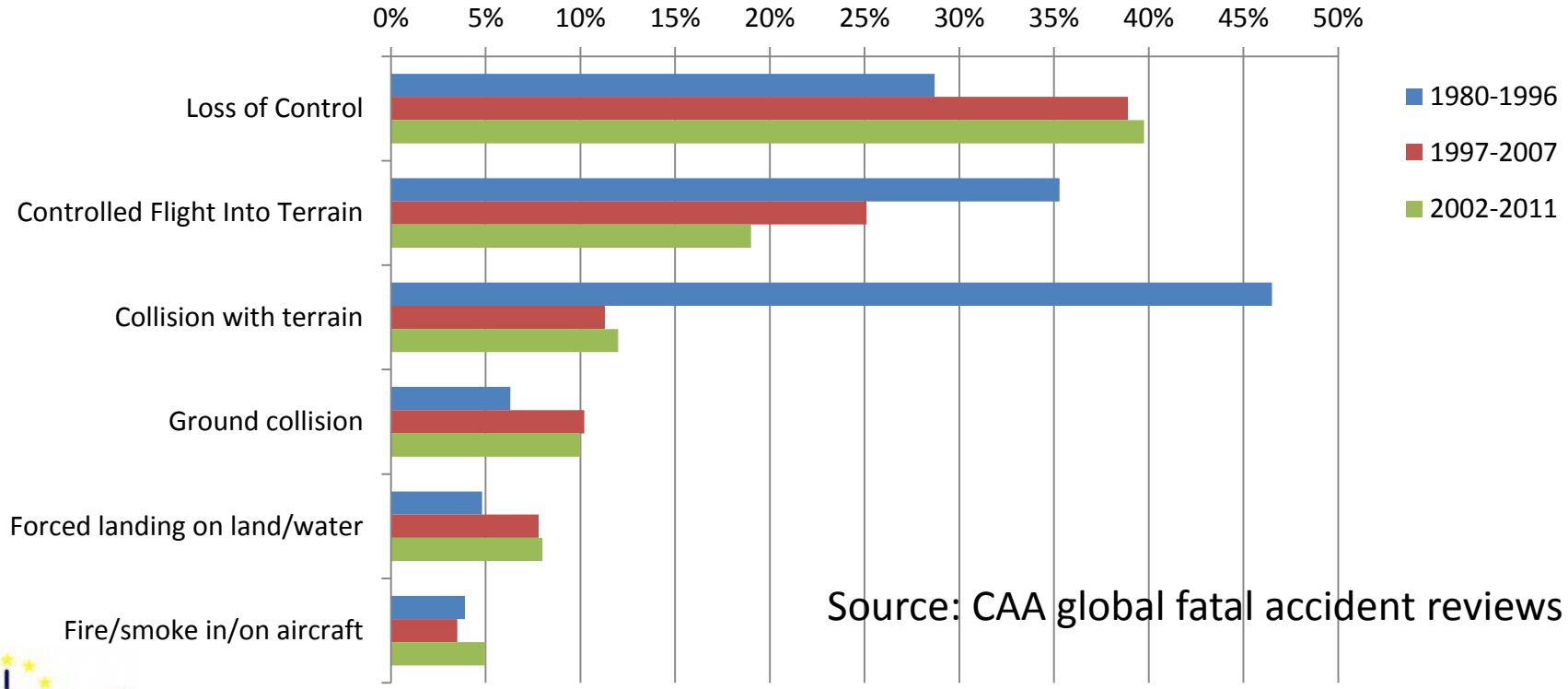
TU Delft

Structure

- Introduction
- Estimation of the Safe Flight Envelope
- Envelope Protection
  including Concept Demonstration
- Ongoing research: Upset Recovery

Introduction

- Loss of control in flight remains the most frequent primary cause of accidents
- 40% of all accidents is LOC-I related and this category involves most fatalities
- Increasing trend over the last decades



Source: CAA global fatal accident reviews

Upset Prevention and Recovery

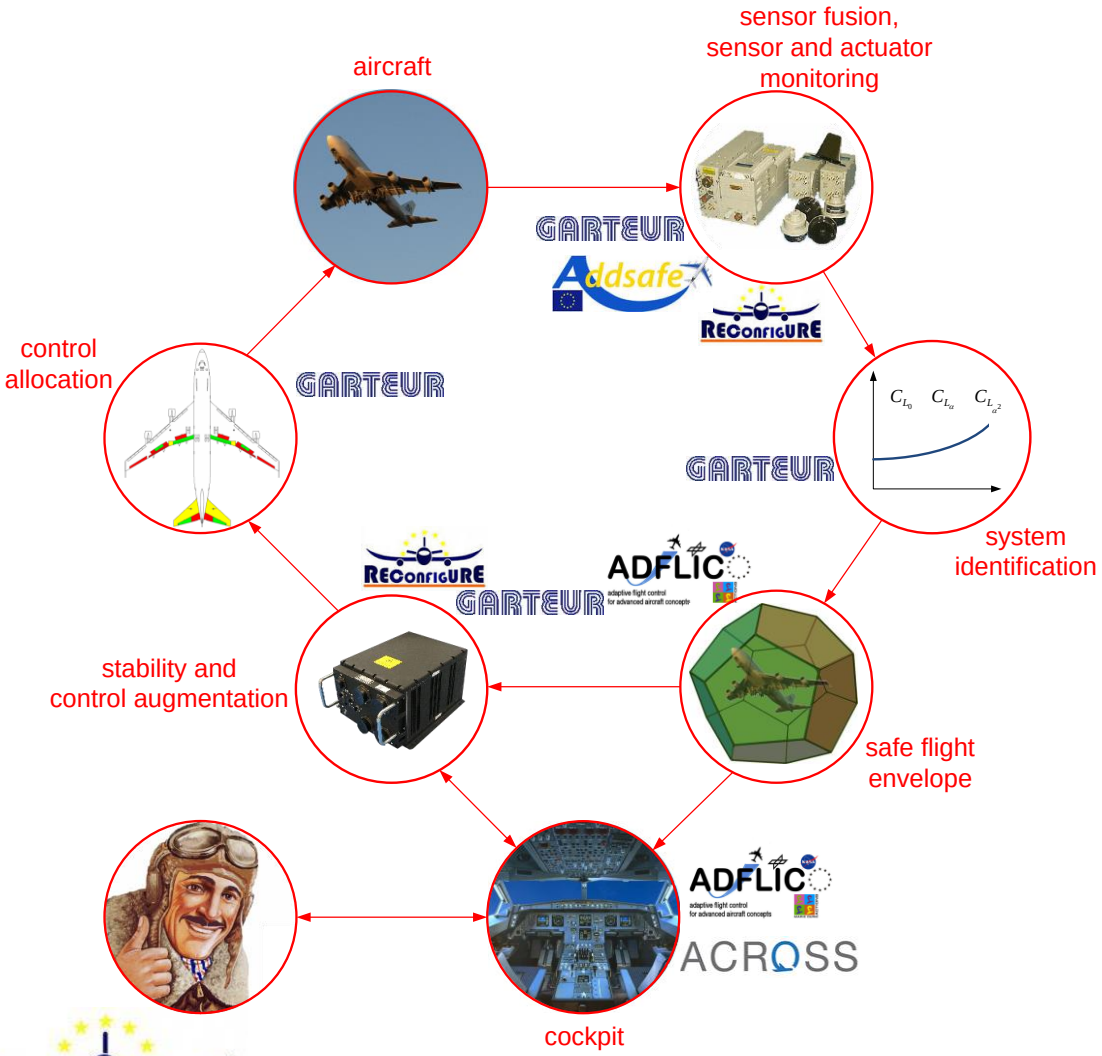
Research subtopics, based on CAST directives on safety enhancements:

order of priorities

1. **Upset prevention**
   - Adaptive safe flight envelope estimation
   - Autoflight trajectory prediction and alerting
   - Adaptive envelope protection
2. **Upset recovery**
   1. Stall recovery guidance
   2. Unusual attitude recovery

Upset recovery training aspect

Reconfiguring flight control



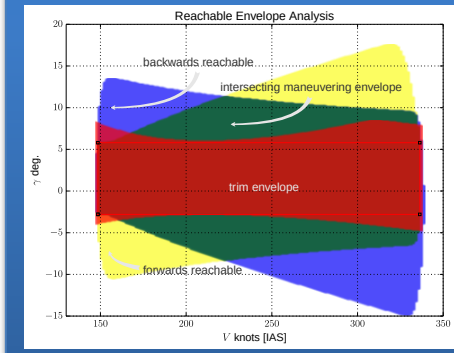
Garteur:
AG-16: Fault Tolerant Flight Control (2004-2007)

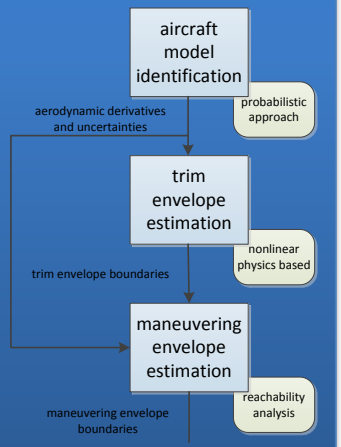
EU-FP7:
ADDSAFE (2009-2012)
RECONFIGURE (2013-2016)
ADFLICO (2012-2015)
ACROSS (2013-2016)

NASA:
IRAC (2006 – 2010)
VSST (2010 – 2014)
TASA (2014 – present)

Upset Prevention

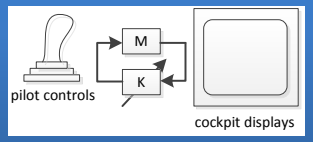
Algorithms



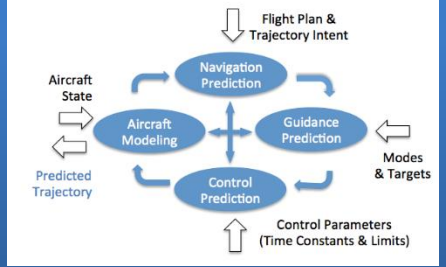


Envelope Estimation

Real-time updates to PFD limits



Adaptive protections and haptic feedback



Trajectory prediction

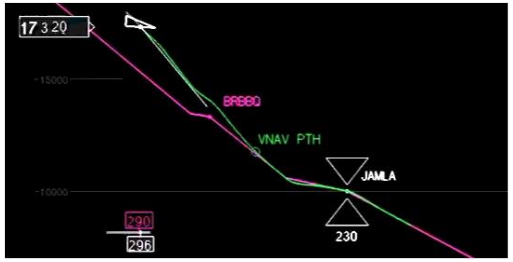
Predictive alerts

Predictive state and mode transition displays

Flightdeck tools



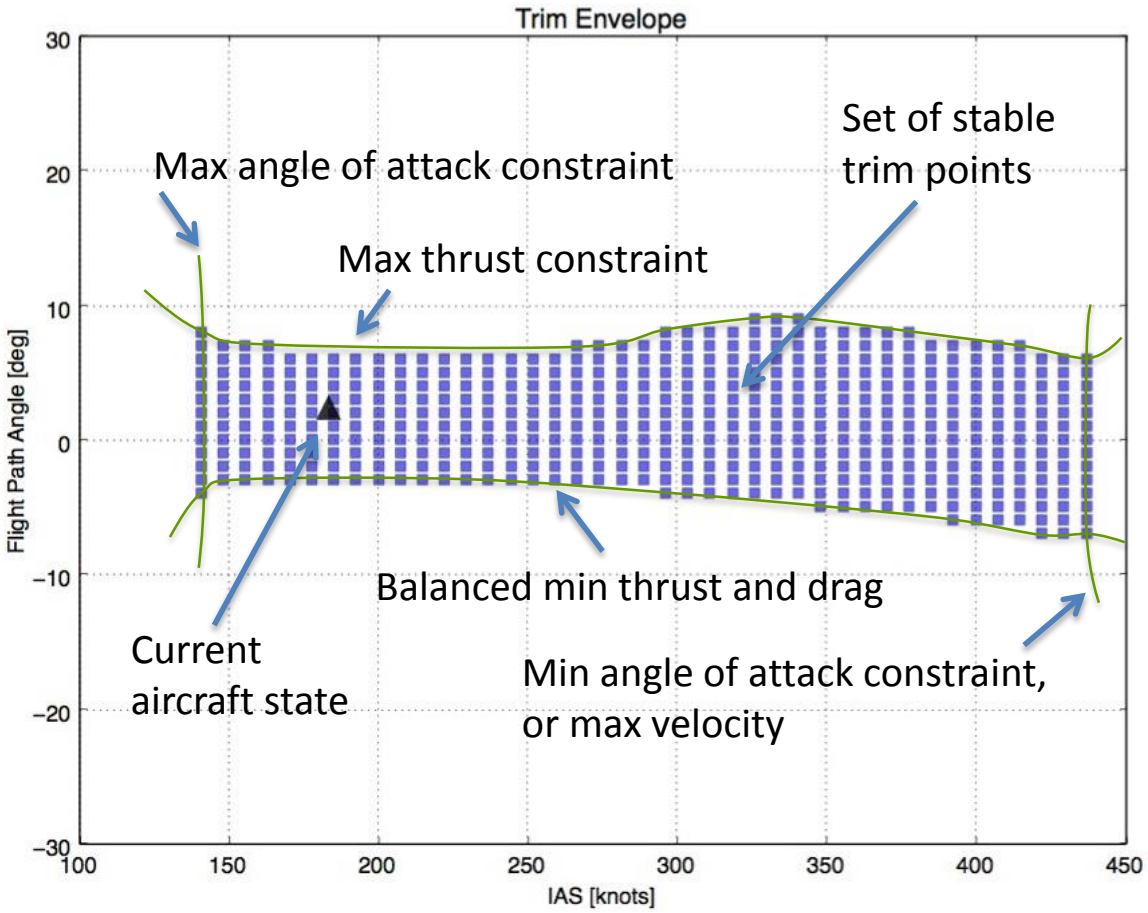




Estimation of the envelope boundaries trim envelope

Trim envelope: all the sets of stable (V,γ) for which $(\dot{V}, \dot{\gamma}) = 0$, where inputs $\alpha_{\min} \le \alpha \le \alpha_{\max}$ and $T_{\min} \le T \le T_{\max}$

The nonlinear aircraft model is made affine in the inputs, which allows an efficient procedure for finding trim points analytically and checking their stability.

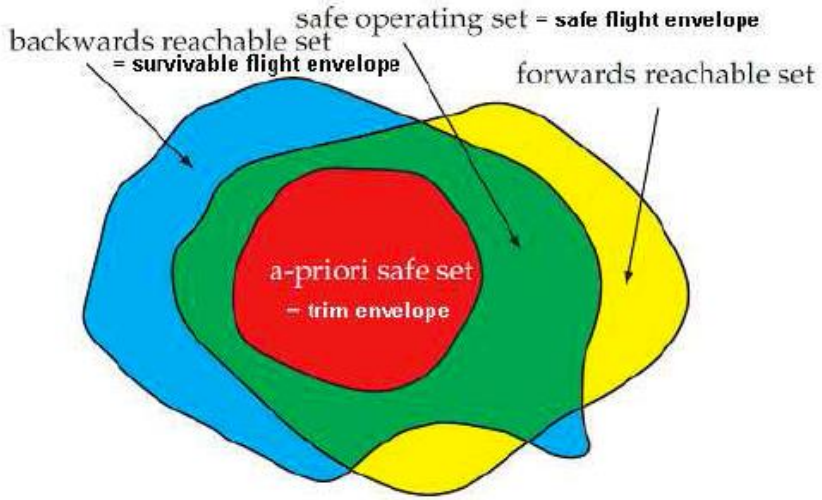


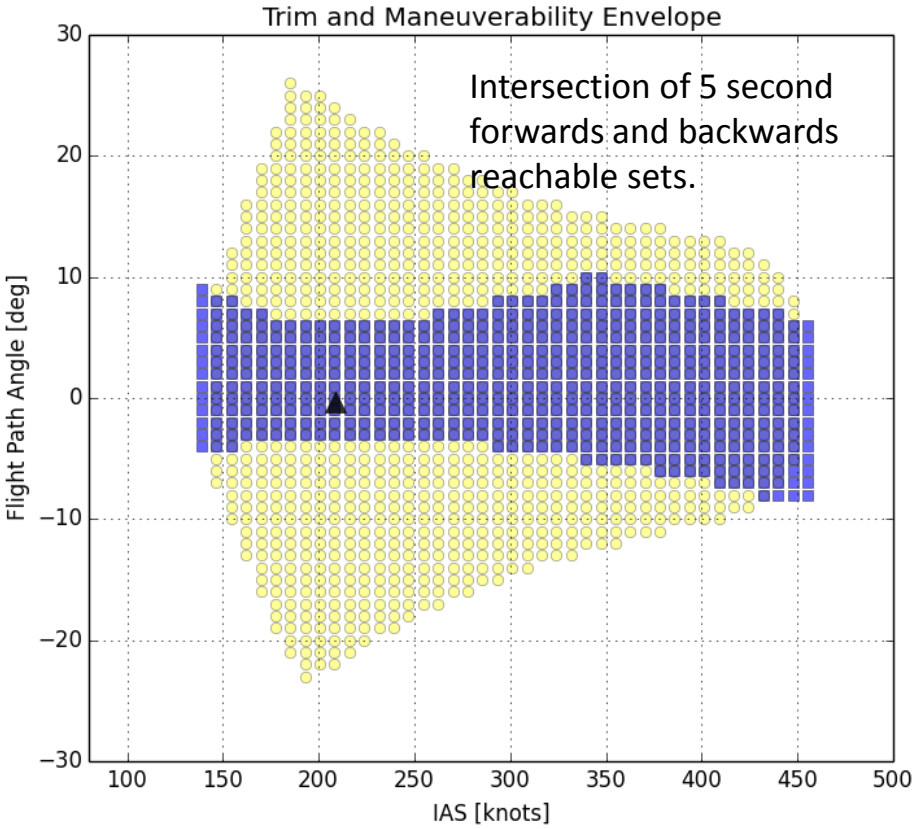
ACT Simulation Model at 15000 feet.

Estimation of the envelope boundaries maneuvering envelope

Safe maneuverability envelope is defined as intersection between forward and backward reachable sets

Robustness for model uncertainty included

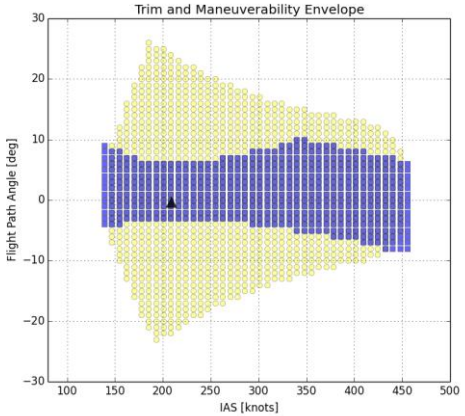




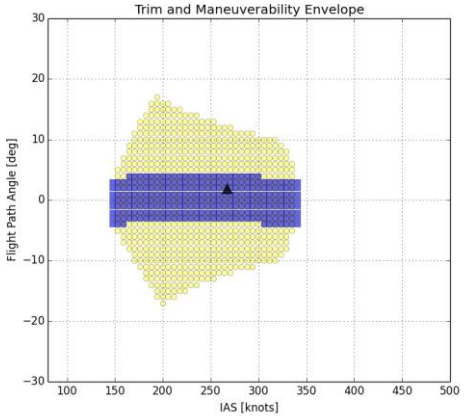
Based on ACT Simulation Model at 15000 ft.

Estimation of the envelope boundaries trim and maneuvering envelope variation

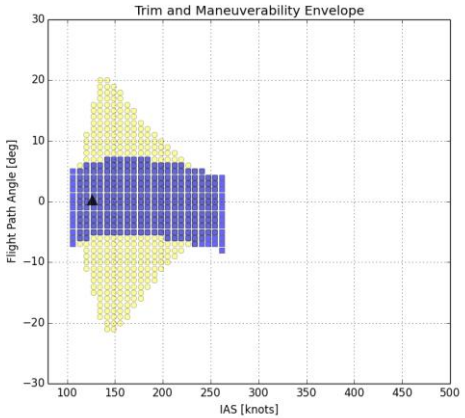
Nominal at 15000 ft.



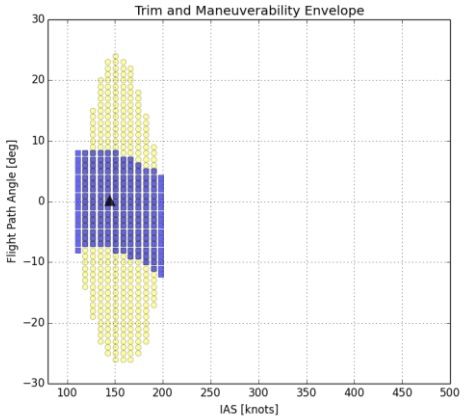
Nominal at 30000 ft.



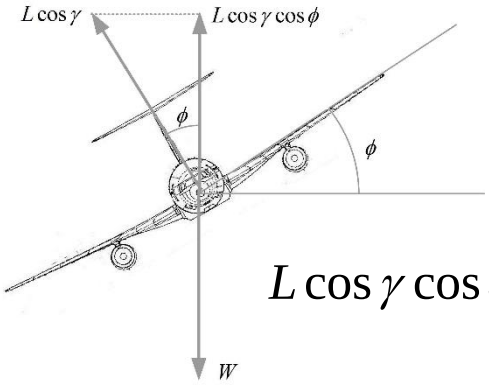
Full Flaps at 15000 ft.



Full Flaps, Gear, Spoilers at 13000 ft.

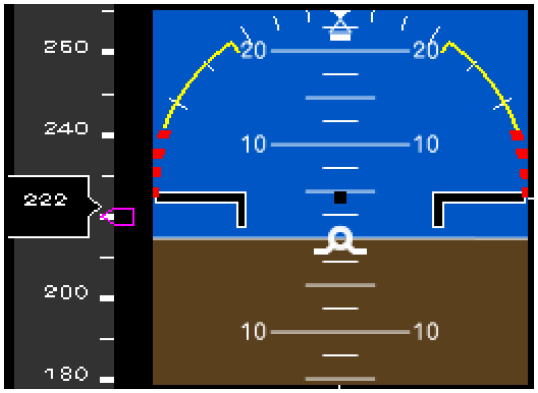


Estimation of the envelope boundaries maximum bank angle

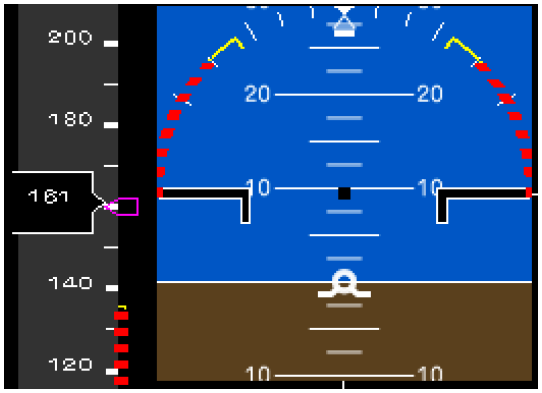


$$L\cos\gamma\cos\phi = W$$

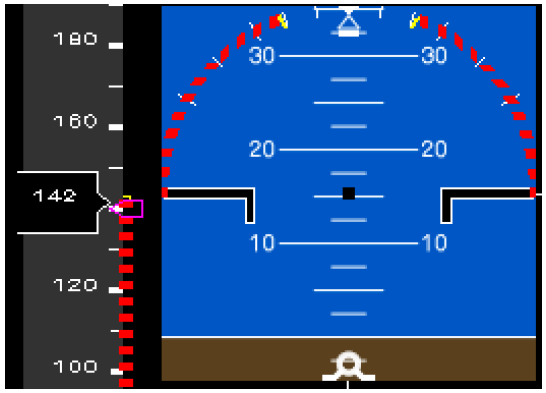
maximum achievable bank angle at current airspeed and flight path angle before stall occurs



V_{IAS} = 222 kts, ϕ_{max} > 60°

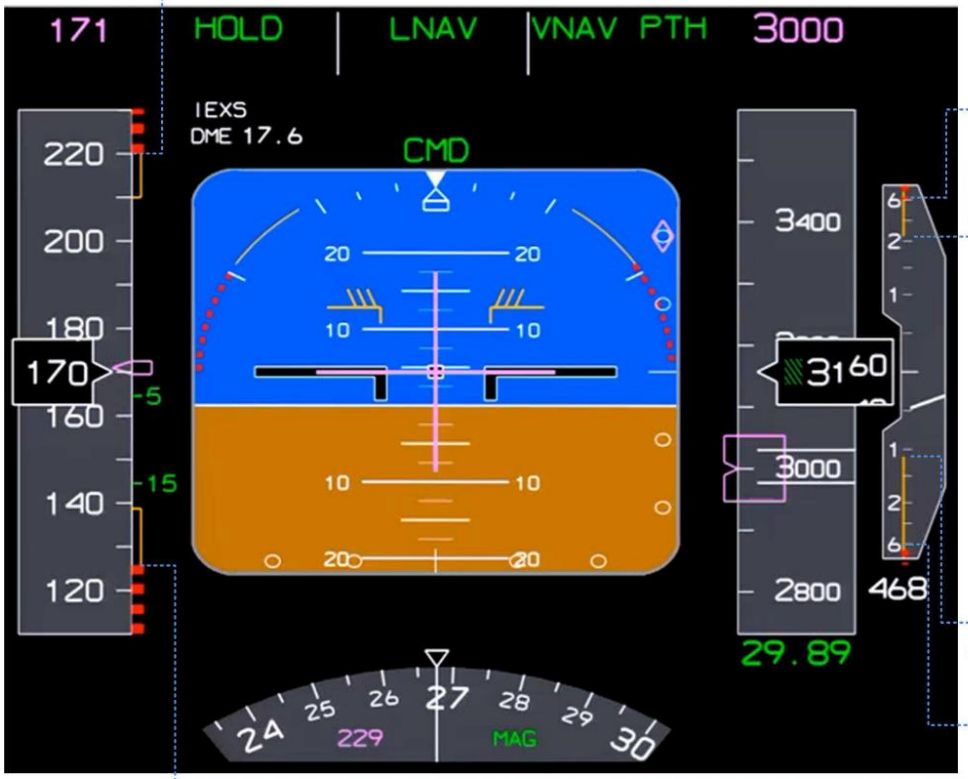


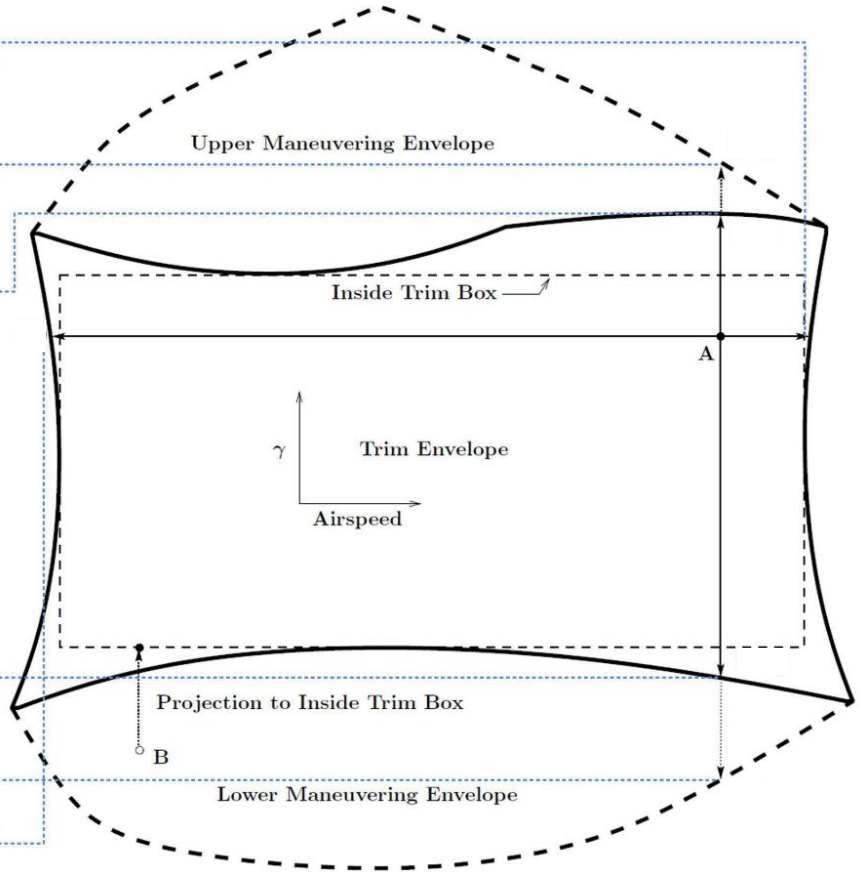
V_{IAS} = 161 kts, ϕ_{max} = 45°



V_{IAS} = 142 kts, ϕ_{max} = 20°

Additional information provided to the pilot over the cockpit displays





Experiment overview: Advanced Concepts Flight Simulator

- Objective

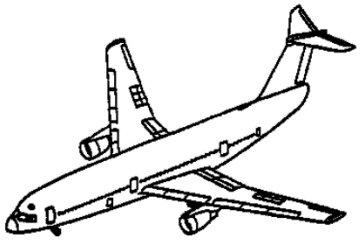
  Explore how crews manage their trajectory and energy state while interacting with flight-deck automation, both with and without new technology

- Overview
  - 10 commercial flight crews
  - 4 “challenging” descent and landing scenarios
  - NextGen compatible routes in Memphis airspace
  - Workload assessment, post run questionnaire, end of study questionnaire
- New technologies
  - Predicted trajectories displayed on the navigation display (ND) and a vertical situation display (VSD)
  - **Maneuver envelope limits displayed on the primary flight display (PFD)**
  - Predictive alerting (on EICAS and ND/VSD)

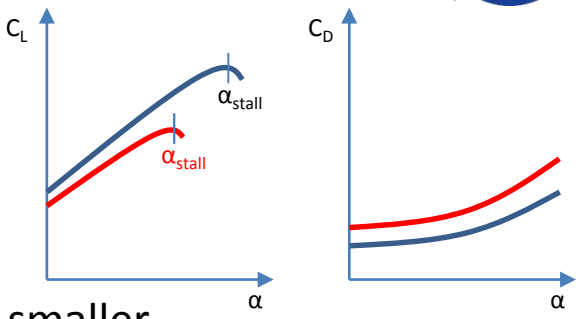




Advanced Concepts Flight Simulator (ACFS)

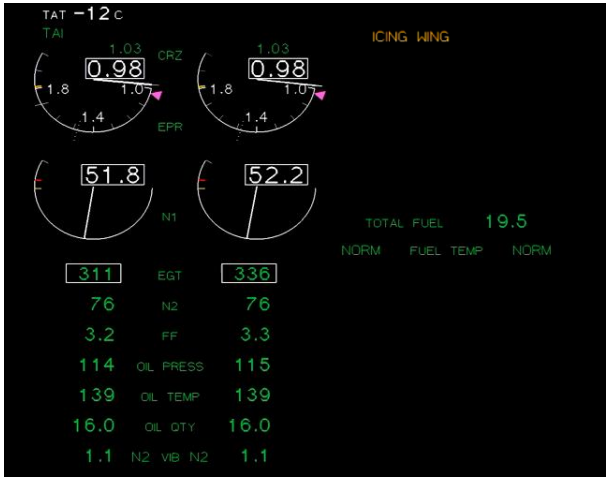


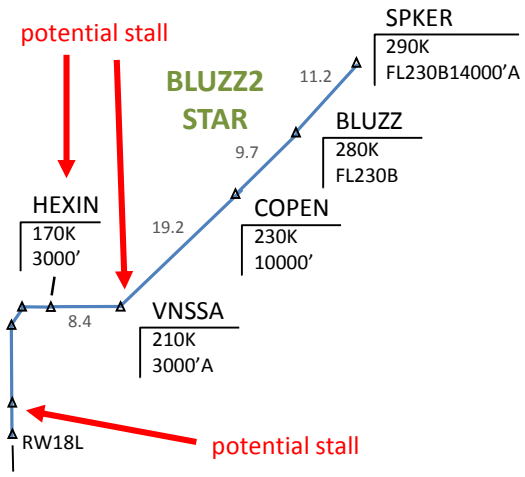
Experiment overview: Icing scenario

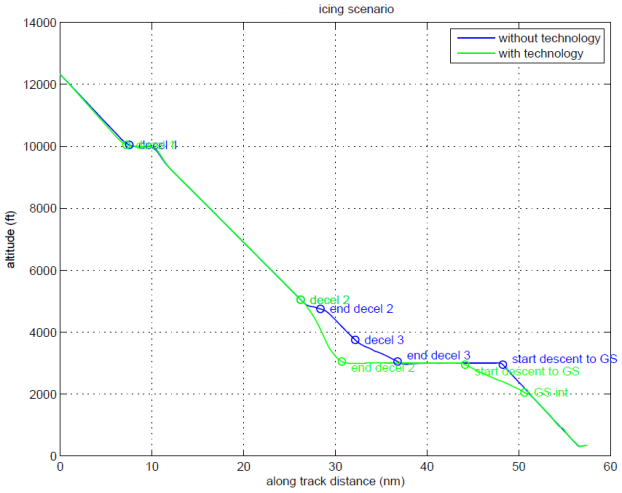


- Aircraft is initialized in an icing condition:

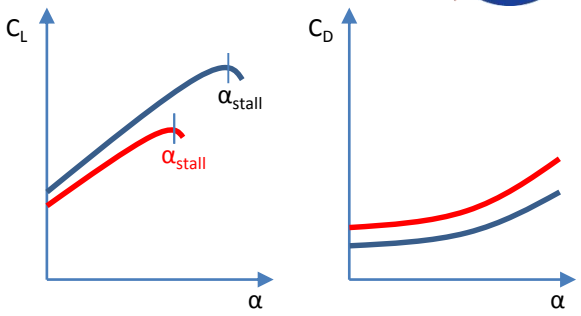
  modified flight dynamics: less lift, more drag, α_{stall} smaller
- Aircraft flies published profile (unless flight crew declares emergency)
- Larger than expected V overshoots during deceleration segments, potential stall, earlier than expected flap deployment needed



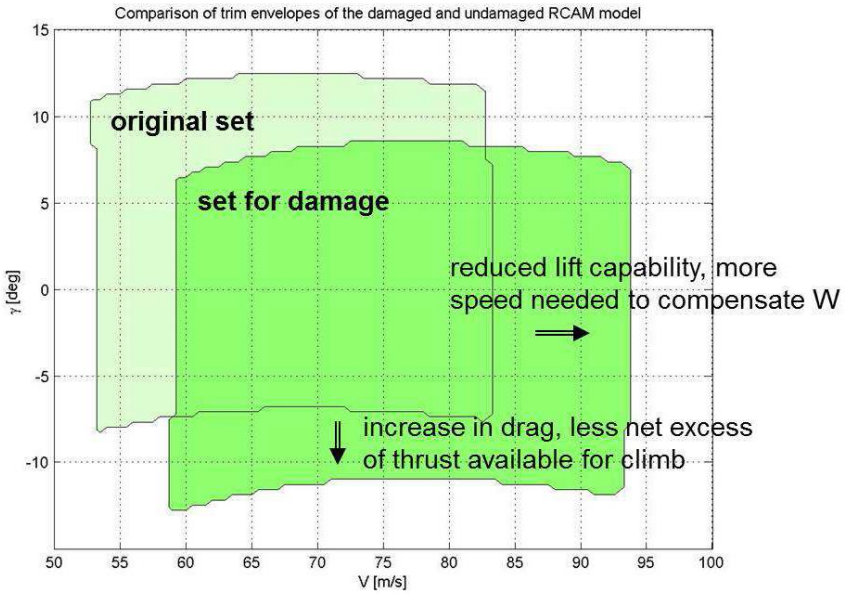




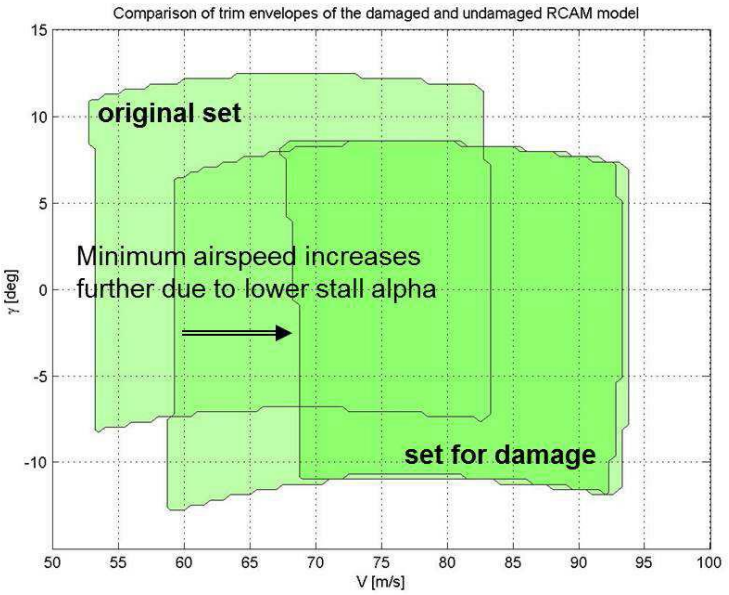
Results
Icing scenario



Impact of icing on the safe flight envelope

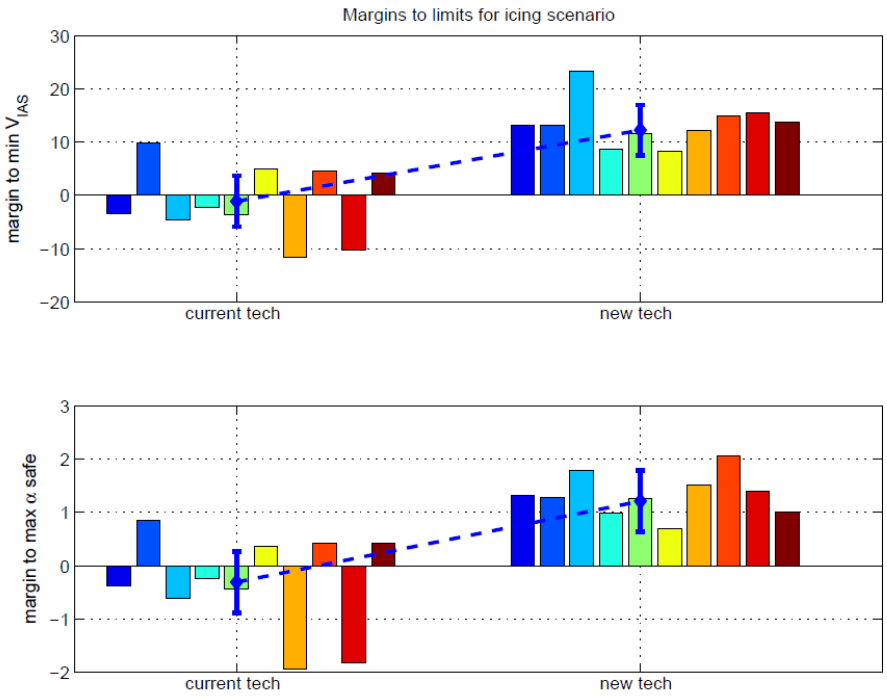


icing effect

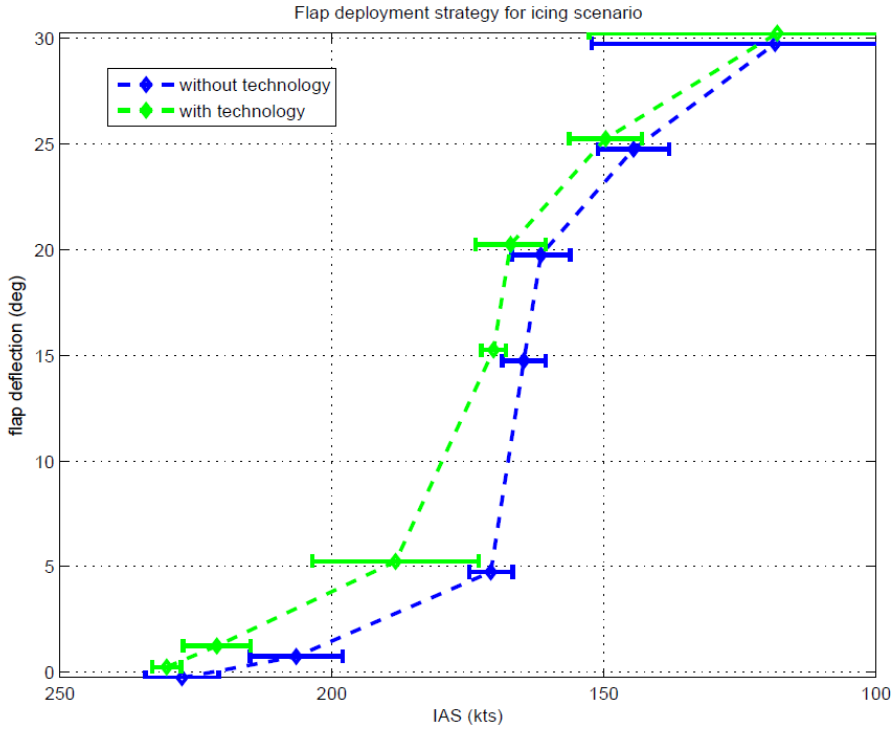


icing effect and reduced α_{stall}

Results
Icing scenario



margins for all crews



flap deployment strategy

Implementation of the protections in the closed loop architecture

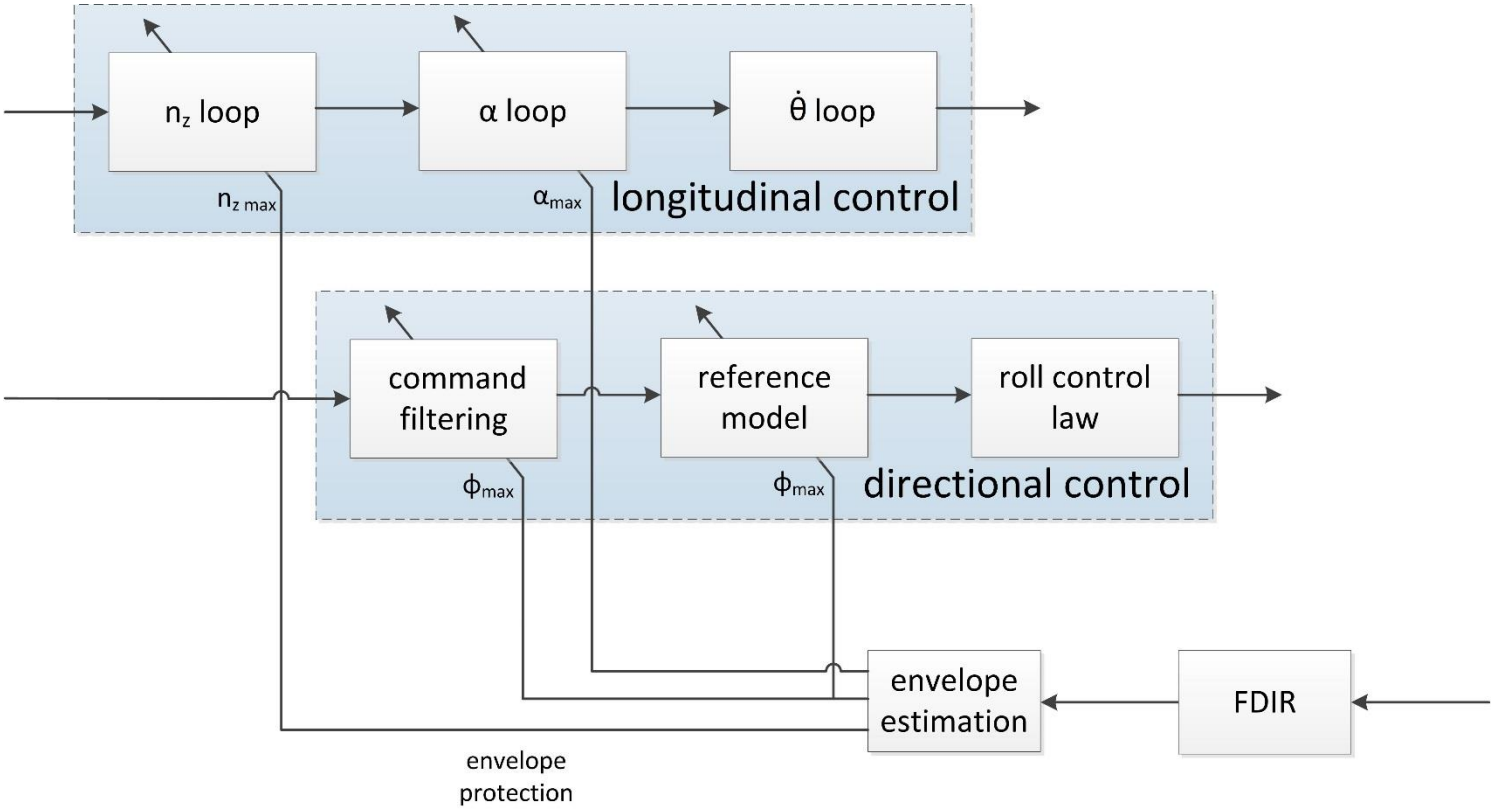
Protections are implemented in:

- Flight control laws
- Cockpit displays
- Haptic feedback

Envelope boundary	Protection in controller	Displayed in PFD	Haptic feedback
max bank	X	X	X
max alpha	X		X
min V_{CAS}	via max alpha	X	via max alpha
max load factor	X		X
min/max flight path angle		X	

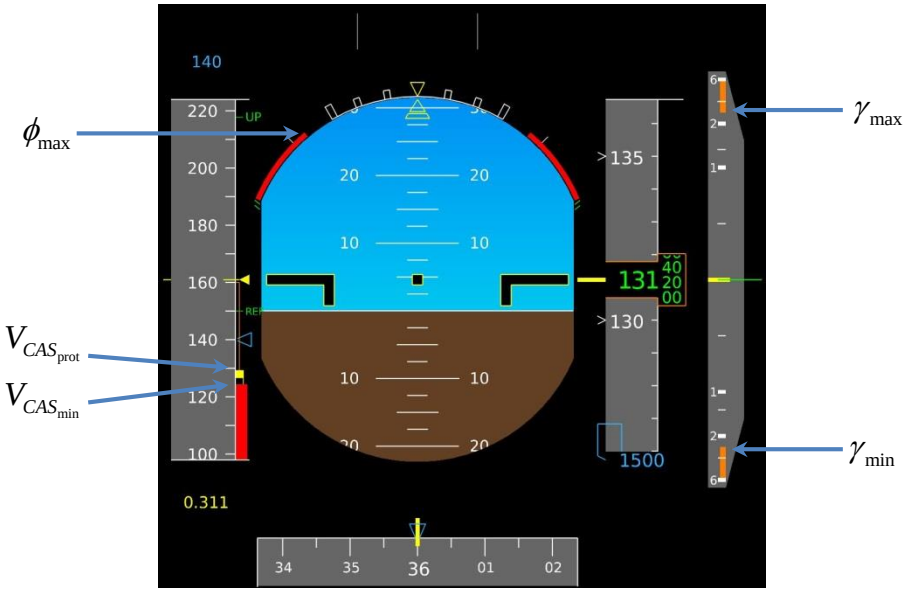
Implementation of the protections in the closed loop architecture

Implementation in controller

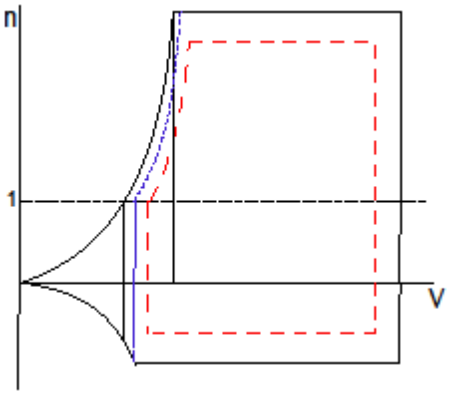


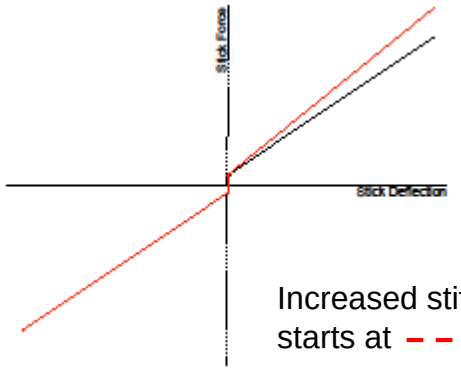
Implementation of the protections in the closed loop architecture

Cockpit displays



Haptic feedback



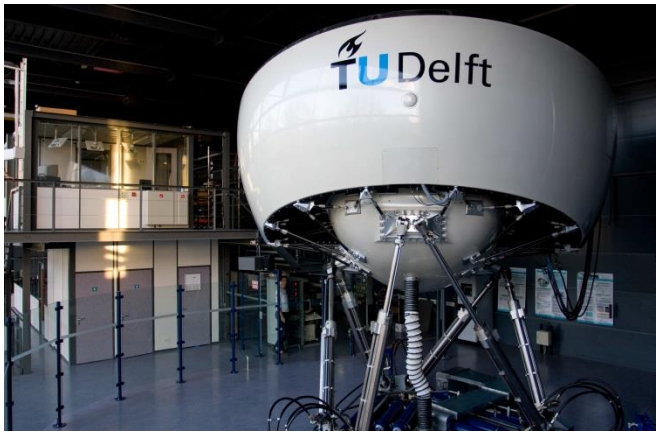


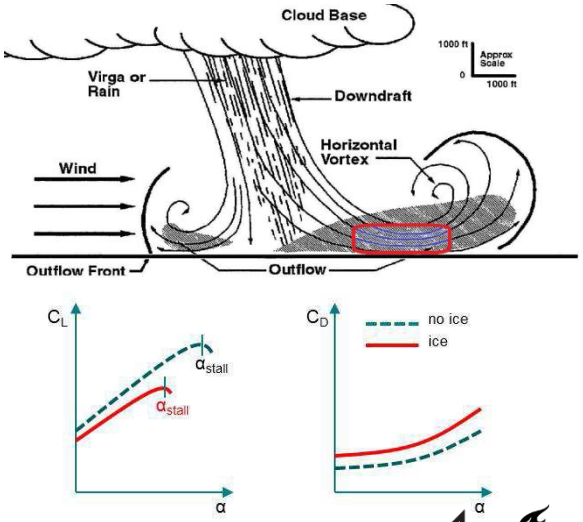
Increased stiffness for stall starts at – – – in envelope



Experiment method: Simona Research Simulator

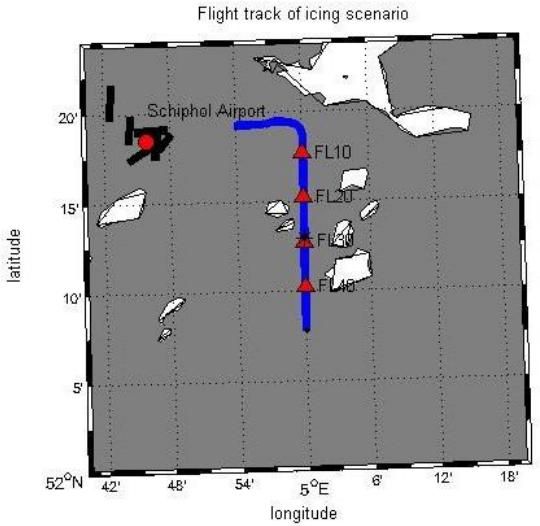
- Research hypotheses
  - Will envelope protection prevent loss of control and reduce workload?
  - Will modified PFD improve situational awareness about flying capabilities?
  - Will haptic feedback improve situational awareness about protective action?
- Overview
  - 7 commercial pilots, type rated for Airbus A330
  - 2 scenarios in approach:
    - Icing near Amsterdam Schiphol Airport
    - Windshear near Nice Côte d'Azur Airport
  - Workload and situational awareness assessment, post run questionnaire, end of study questionnaire
- New technologies
  - Adaptive envelope protection in flight control laws
  - Extended primary flight display
  - Haptic feedback on stick

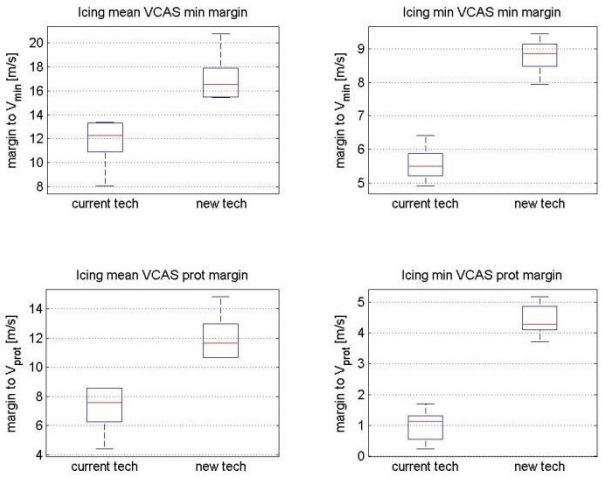


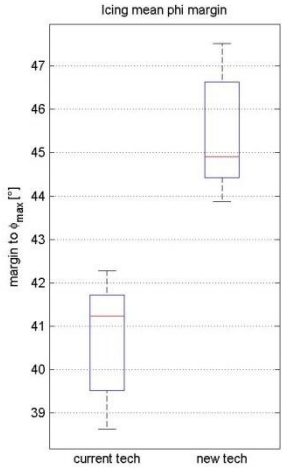


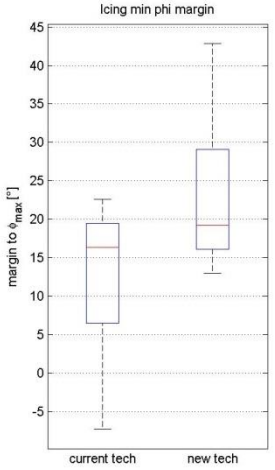
Results: icing scenario

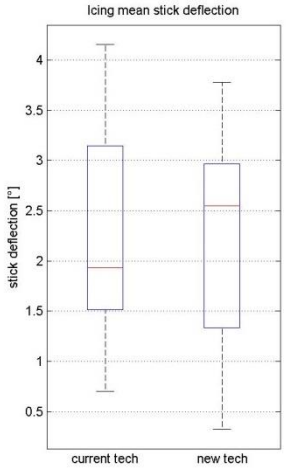
- Gradual ice accretion on the wings, starts around FL30
- Wind gusts make effect on envelope less obvious
- Speed and bank angle margins improve with new tech
- No increase in workload

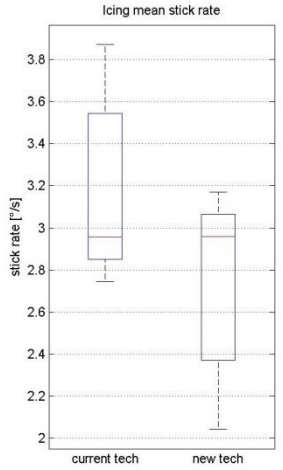






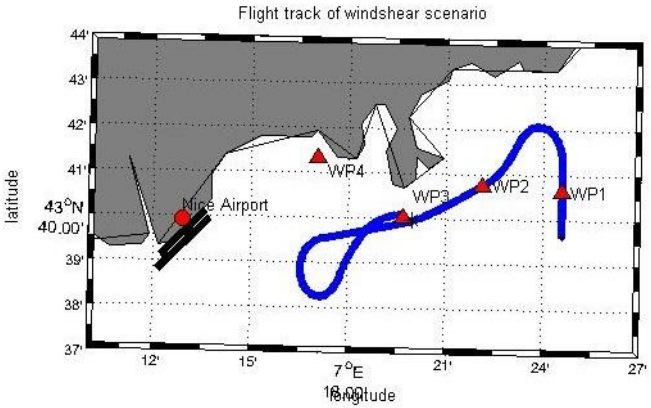


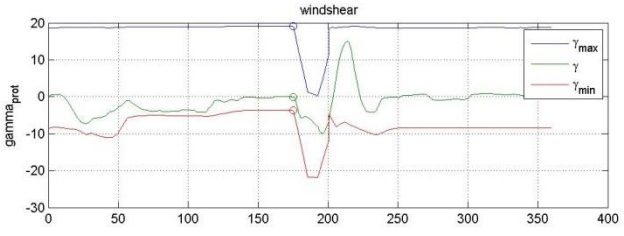


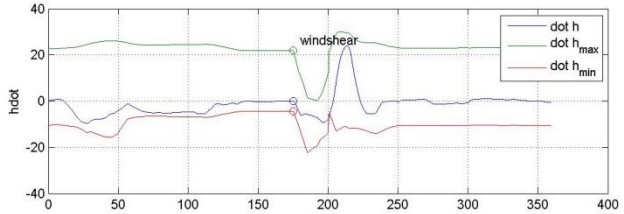


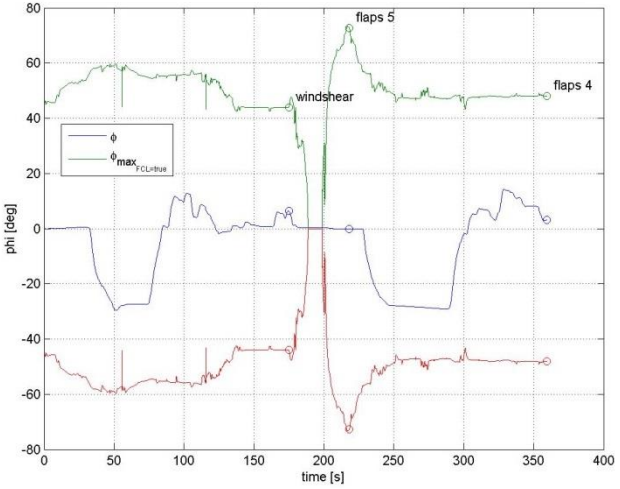
Results: windshear scenario

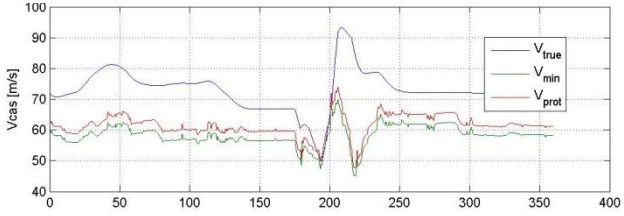
- First downwash, followed by tailwind around WP3
- Envelope boundaries updated for windshear
- No noticeable difference in pilot performance
- Pilots stick to their windshear recovery procedure

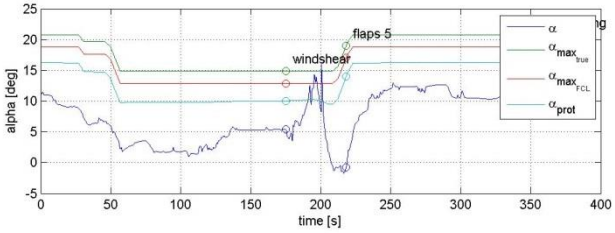








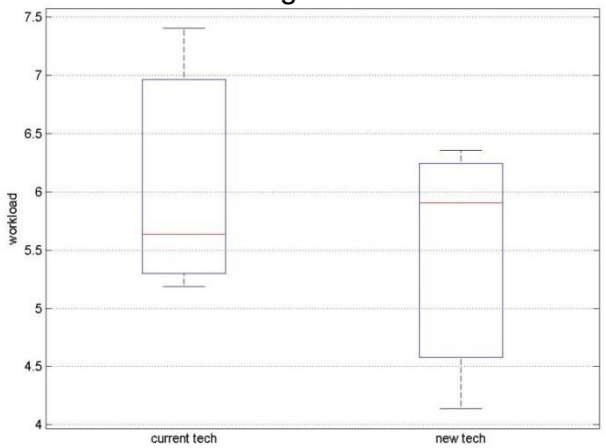




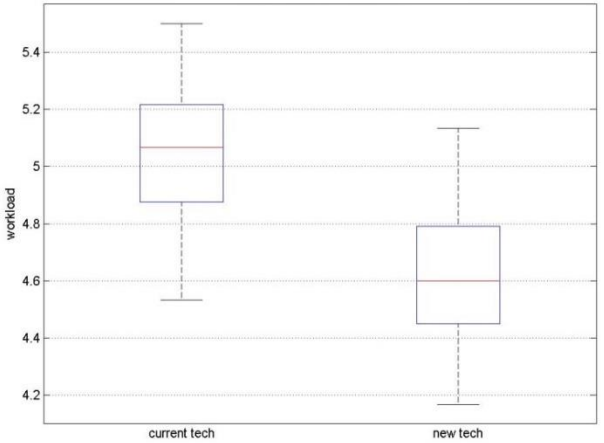
Results: pilot feedback

- NASA TLX workload ratings:

icing scenario

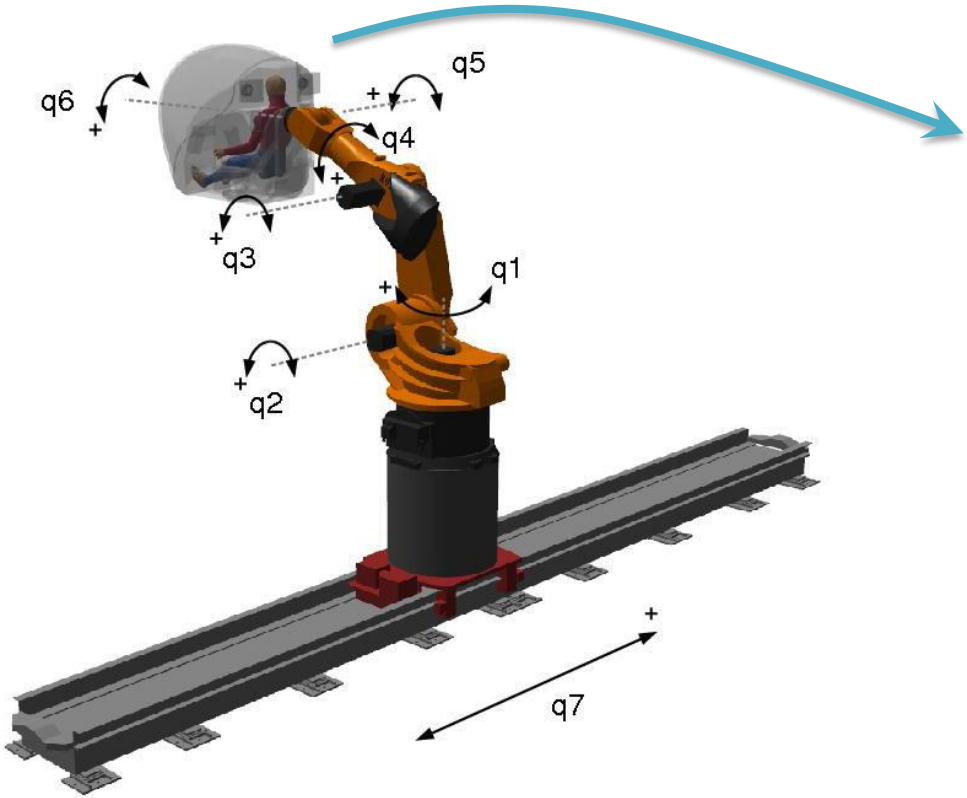


windshear scenario

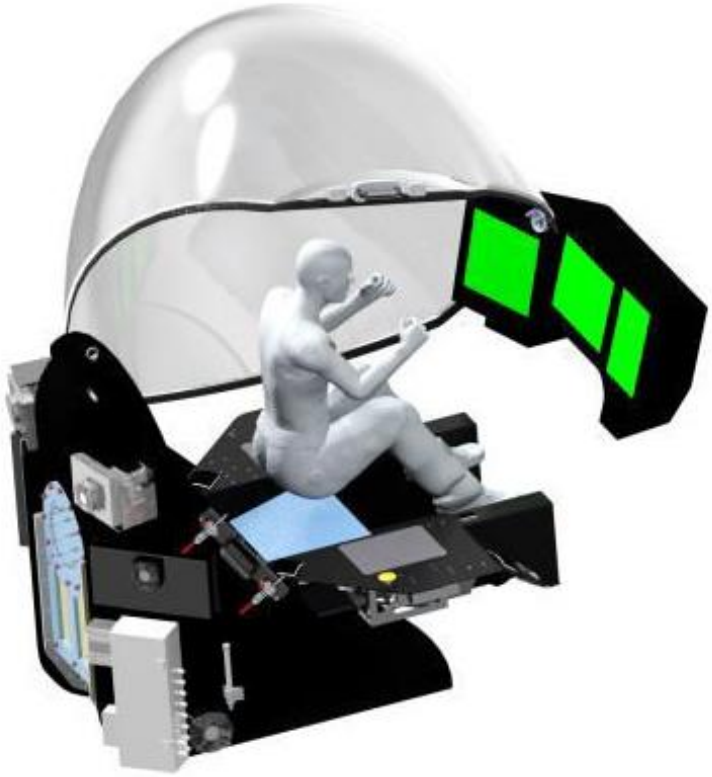


- Few confusion about envelope protection automation
- Usefulness of indicators: V(PFD) – V(haptics) – nz(haptics) – φ(PFD) – Vz(PFD)
- Awareness increase by new envelope limit indications
- No fighting of the control system for icing as well as windshear
- Good confidence about true envelope edges, based on information presented

Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen

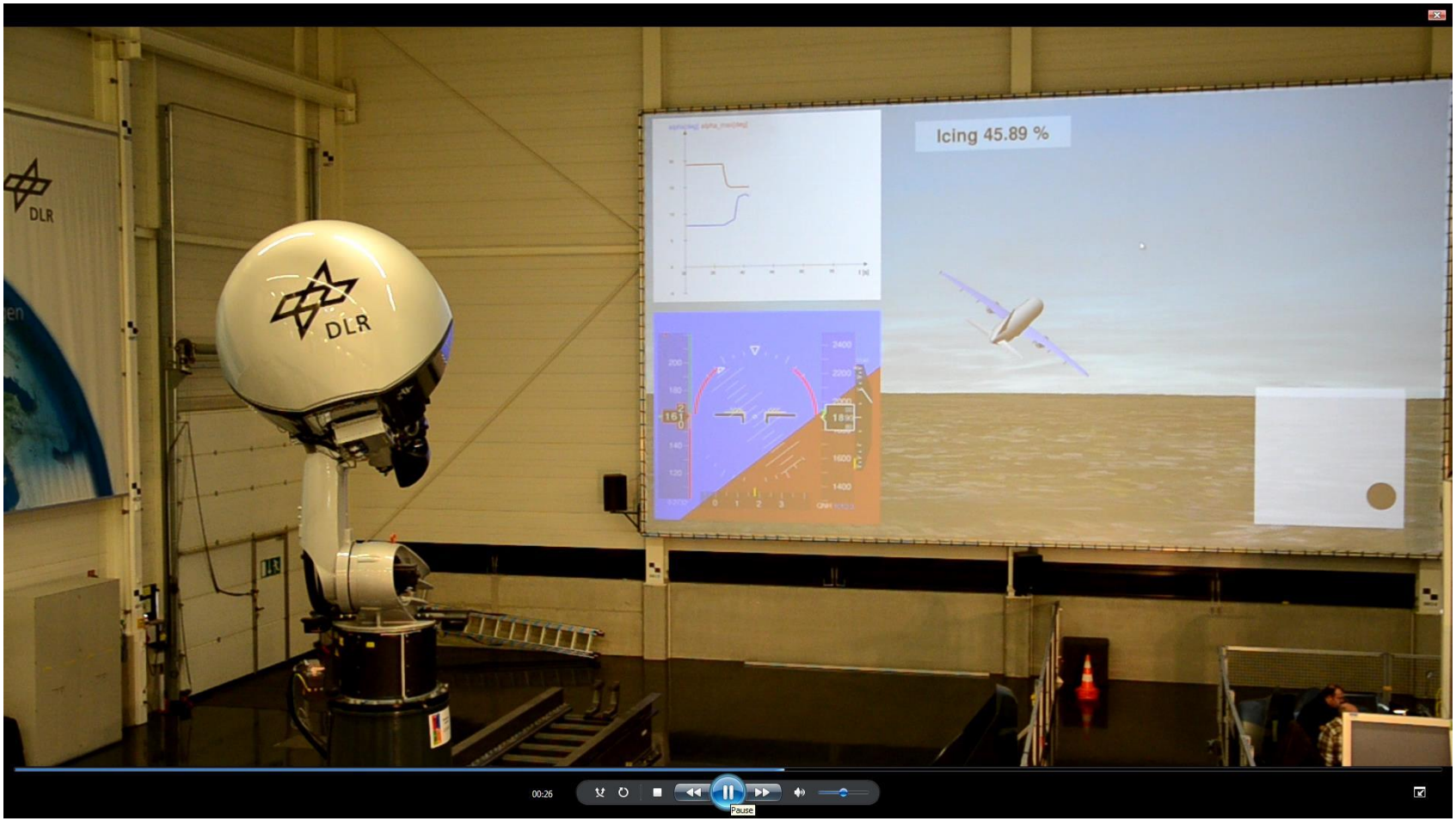


DLR Robotic Motion Simulator: overview



Simulator cab of
Robotic Motion Simulator

Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen



Conclusions of upset prevention and recovery

- Adaptive safe flight envelope estimation and protection algorithms have been designed and evaluated by several professional commercial airline pilots in various relevant simulation environments
- Safe envelope bounds estimated in real time taking into account malfunctions and upsets, used for three kinds of protections:
  - Extended Primary Flight Display → Experiments in ACFS
  - Hard protections in the flight control laws → Experiments in Simona
  - Haptic feedback on sidestick
- Significant performance changes detected in icing scenario, not so much for stabilizer misalignment or windshear.
- Observations with new technology:

ACFS experiments:

pilots adapted strategy based on information

Icing scenario:

- higher V_{min}
- flap deployment for higher speeds

Simona experiments:

- larger safety margins to envelope boundaries prevent loss of control in off-nominal conditions,
- reduced workload (objective and subjective ratings),
- improved situational awareness (subjective ratings).

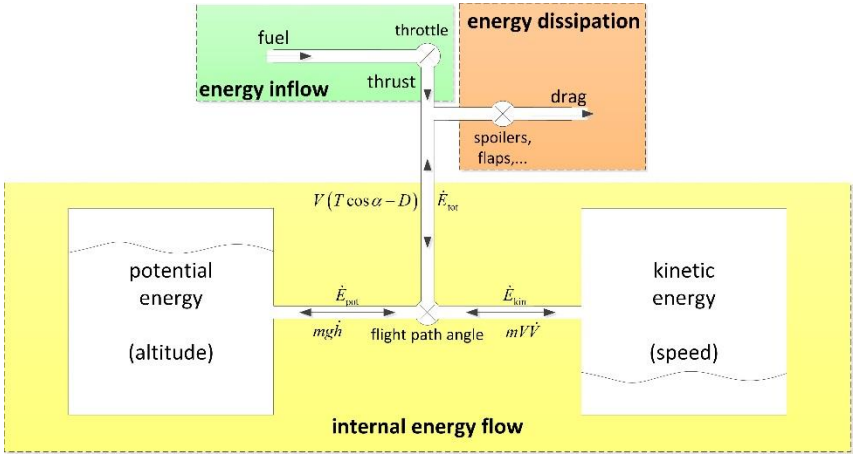
Upset recovery: stall recovery guidance

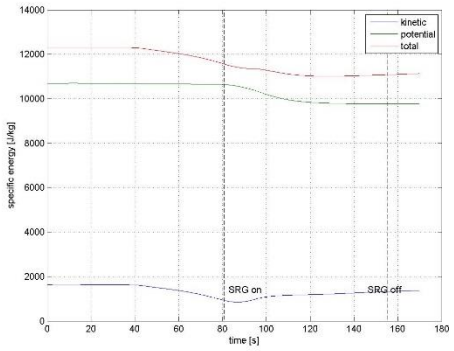
Strategy: exchange potential energy (altitude) for kinetic energy (speed), taking into account energy dissipation (drag) and energy inflow (thrust)

Constraints:

- Secondary stalls (α)
- Structural loads (n_z)
- Pitching moment (T_{max})

Pilot guidance through flight director (θ_c) and throttle tape (T_c) in PFD



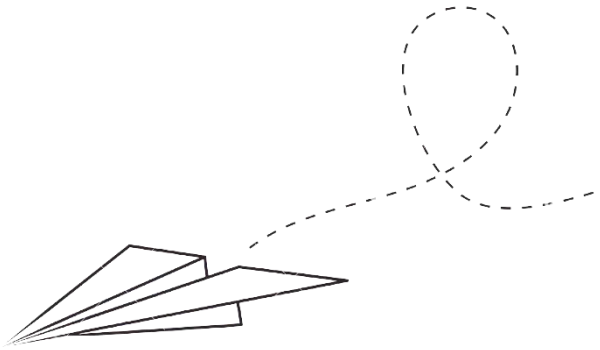




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Upset prevention

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Upset recovery

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